3D PRINTING POLYMER FIBRE CONCRETE

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ABSTRACT

A 3D concrete printer has been designed and built by the authors to enable research on a range of concrete and fibre concrete materials. A range of cement-based materials are developed in order to determine the appropriate rheology for 3D printing of concrete (3DPC). Particular attention is paid to thixotropic behaviour. The viscosity of stiff, dough-like (fibre) concrete is reduced by the pumping shear action, after which the viscosity is restored directly after printing. This is essential for shape retention and buildability of the printed shape. Fibre concrete, ranging from low fibre content for plastic shrinkage crack control, to moderate content such as in strain-hardening cement-based composites (SHCC) presents the challenge to retain good fibre dispersion and orientation in the 3DPC process. Results of 3D printing (3DP) of fibre concrete at SU are presented, including the beneficial influence of fibres on plastic shrinkage without changing the initial and final setting time, whilst retaining the mechanical strength and stiffness properties in the hardened state.

KEYWORDS:

3D printing of concrete; Fibre concrete; Thixotropy; Free form.

INTRODUCTION

Early reports indicate that 3DPC can significantly reduce construction times and waste, while also increasing architectural freedom and aesthetics through its ability to produce geometrically-complex structural elements. Successful industrialisation in various parts of the world may be explained by the automation processes which led to a faster and cheaper way of production. The construction sector is not automated to the same extent. Nevertheless, traditional mixing and casting on site has to a significant degree been replaced by pre-cast construction in several developed and newly industrialised countries. Further significant benefit from automation by 3DP in construction is foreseen in terms of reduced or redundant formwork, which may comprise 35-54% of construction cost and consume 50-75% of construction time (Jha 2012), and little or no waste material compared with significant current construction waste and landfill demand (Lawson et al. 2003, van Zijl 2010). The concept was introduced as a means of rapid prototyping (Hull 1986, Chua and Leong 2014) with the underlying principle of additive manufacturing (AM), it is forming structures or parts layer by layer. Successes with 3DP of geometrically complex and highly customised metal and plastic products promise opportunities also for the construction industry (Gardiner 2011). Experiences with pumping (Wallevik 2002, Jolin et al. 2009, Mechtcherine et al. 2014) and extrusion (Shao & Shah 1997, Visser & van Zijl 2007) and the associated concrete technology have contributed to develop 3D printable concrete (van Zijl et al. 2016, Paul et al. 2018).

Appropriate rheology for 3DPC is required to enable pumping, extrusion through the nozzle, and retention of the shape despite the weight of subsequent layers, considering the cost-benefit of fast construction. Typically this requires of the concrete to have a high static shear flow resistance, but low dynamic shear flow resistance when agitated or pumped, and rapid restoration of high static shear resistance once extruded. This thixotropic behaviour (Barnes 1997, Roussel 2006) can be achieved through careful mix design.

This contribution reports on 3DP of fibre concrete with a printer designed and built at Stellenbosch University in 2017-2018. It should be noted that maximum aggregate particle size is a typical limiting pump specification, as is fibre length as reported by De Beer & van Zijl (2016). This requires that a 6 mm short fibre, instead of a more widely used 12 mm fibre for standard casting application is selected here. Thixotropy of the concrete developed is characterised by rheometer test results. Given arid South African climatic conditions, concerns about concrete construction without protective formwork are addressed by studies on plastic shrinkage under extreme conditions of high temperature, wind and low relative humidity, following Combrinck (2012) and Combrinck & Boshoff (2013). The effect of low volume polymeric fibre reinforcement on plastic shrinkage, setting time and mechanical strength and stiffness is investigated. Finally, 3D printed elements are reported with increasing layer dimensional stability, and overall structural stability at increasing 3D printing rate.

DEVELOPING A 3D PRINTER FOR FIBRE CONCRETE

A laboratory size gantry-type 3D printer with outer dimensions 1.3 x 1.3 x 1.67 m (w x l x h) was designed and manufactured by PhD-candidate PJ Kruger, with assistance of the Mechanical Technologist Mr Johan van der Merwe in the Structures Laboratory of the Civil Engineering Department of Stellenbosch University. The 3D concrete printer has a build volume of roughly 1 m^3. Paired with a powerful 3-phase pump, the printer is capable of extruding a range of materials with varying rheology. This enables the research team to produce laboratory scale structural elements and specimens (walls, beams and columns) for testing, ultimately contributing towards fundamental research in the 3DPC industry. The 3D concrete printer is shown in Figure 1, after a design and manufacturing period of 5 and 7 months respectively. The gantry printer has three translational degrees of freedom (DOF), with the option to include rotational DOF in future to enable intricate geometrical detail with alternative nozzle shapes. A 25 mm diameter nozzle is fitted for simplicity to allow uniform cross-section printed layers around bends in the absence of rotational DOF. Careful structural design for robustness and provision for heavy printing of large cross-sections through a nozzle diameter of up to 100 mm, led to the selection of 100 x 50 x 3.5 mm industrial grade steel tubing for the main gantry elements. Linear guide and rail systems mounted on the gantry and vertical sections allow accurate and low friction movement in the x, y, z axes. A belt and pulley system driven by stepper motors facilitates movement along the horizontal axes, while ball screws are the preferred mechanism for vertical movement of the gantry. Mechanical design included deflection limitation and buckling of elements, as well as vibration under heavy printing loads accelerated and decelerated for adequate printing speed and control. A microcontroller unit (MCU) shown in Figure 1 is the core of the 3D printer, powered by a 12 V power supply unit (PSU), with sufficient power to accommodate also other electronic features like fans and lighting. A trolley with 12 polyurethane wheels of 700 kg ultimate capacity each facilitates stable printing, and subsequent easy removal and transportation of printed elements. Limit switches connected to the MCU control printing limits for safety and calibration. The final component is a 3-phase 380 V 3 kW locally manufactured concrete pump (Rockcrete TSL), originally purchased for research on sprayed application of fibre concrete. A variable frequency drive (VFD) was added in order to control the pump motor speed.

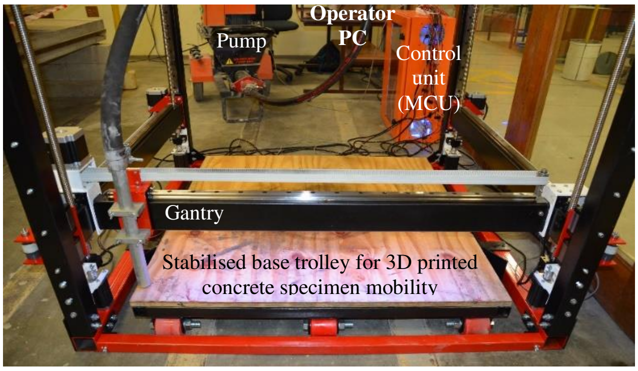


Figure 1: 3D concrete printer component layout and final assembly

THIXOTROPIC MATERIAL BEHAVIOUR

Advanced material science knowledge is required to develop concrete suitable for 3D printing. Thixotropic behaviour, which is a time-dependant shear thinning rheological property, is essential for optimum concrete printing. Highly thixotropic materials require less pumping pressure for transportation, while also yielding sufficient buildability in terms of layer and structure stability and deformation. The primary thixotropic indicators for a suitable 3D printable material are the static and dynamic yield shear stress, each respectively influencing buildability and pumpability. The degree of thixotropy of a material is directly related to the difference in these shear stress properties. Figure 2 depicts the thixotropic behaviour of the SU 3D printable mortar via a stress growth test conducted with the ICAR Plus Rheometer.

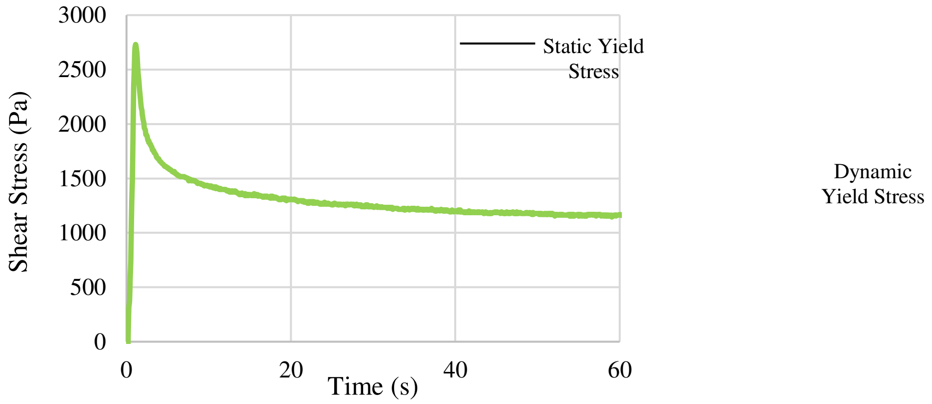


Figure 2: Thixotropic behaviour of the 3D printable mortar developed at SU. The material is characterised by a high static yield stress and a relatively low dynamic yield stress.

PLASTIC SHRINKAGE CONTROL BY FIBRE

Motivation

Plastic shrinkage is a volume change induced by evaporation of the free water within pores of a concrete matrix once the bleed water evaporates. Conventional concrete used in bridge decks, highway pavements and large concrete slabs with large exposed surfaces promote higher evaporation rates and are expected to be susceptible to plastic shrinkage (Kwak and Ha 2006). Plastic shrinkage cracking may be induced if the plastic volume change of the fresh concrete is restrained.

In the AM method of 3D printing, the lack of formwork may expose the printed concrete to higher evaporation rates. In addition, free-form construction may cause differential settlement, which contributes to cracking. Synthetic fibre is usually added to control plastic shrinkage and settlement cracking. A test program is carried out to investigate the influence of polypropylene fibre in a dosage range up to 0.3% by volume, or roughly 2.7 kg/m^3, which is an upper limit of fibres used in industry for this purpose.

Method

The plastic shrinkage climate chamber shown in Figure 3 was designed by Combrink (2012) at SU to simulate various environments for plastic shrinkage and cracking. To represent arid weather conditions in South Africa, a high air temperature, wind speed and low relative humidity are consistently controlled by heating elements, axial fans and dehumidifiers. Here, a 40 °C air temperature, 20.2 km/h wind speed and 10% relative humidity are maintained during the test period to simulate extreme conditions. These factors can be converted into an estimated evaporation rate of 1.05 kg/m^2/h (Uno 1998).

The plastic phase of a concrete material is characterised by means of the Vicat penetration test method described in SANS 50196-3 (2006), which determines the initial and final setting time. Mortar mixes containing different fibre dosages are prepared in the setting mould and enclosed with an evaporation cover to prevent water loss. The specimens are retained in the testing compartment of the climate chamber. The Vicat penetration test is conducted in 20 minute time intervals until the initial setting time is reached, which is defined by penetration readings of 6 ± 3 mm from the bottom of the mould. The final setting time is recorded when no circular ridge is imprinted on the mortar for the first time, as per the SANS standard. The climate chamber test compartment can accommodate 4 PVC plastic shrinkage moulds. The 300x300x100 mm moulds are instrumented with linear variable displacement transducers (LVDTs). Two LVDTs measure horizontal shrinkage deformation as shown in Figure 3. The sum of the two LVDT measurements is the total horizontal shrinkage deformation.

Mix design and specimen preparation

As described in previous sections, a thixotropic concrete material is suggested for AM construction without formwork, in order to support its self-weight and those of subsequent layers. The mix designed here contains fine aggregates only, with particle size less than 4 mm. Due to the low water to cement ratio (w/c = 0.4), chemical additives are used to reach the required thixotropic behaviour shown in Figure 2. The mix ingredients and proportions are shown in Table 1. It must be noted that this can be classified as a high performance mortar, for the purpose of this research program. However, a range of mortar and concrete grades are envisaged in subsequent research.

Locally available Polypropylene fibres with relative density 0.91, length 6 mm and diameter 40 μm (Corehfil 2016) are used. To investigate the influence of fibres on plastic shrinkage, three different fibre volume contents (V_f) are tested, namely 0% (control), 0.15% and 0.3% of the volume of the concrete mix. A standard laboratory pan mixer is used. Directly after mixing, the fresh concrete is cast into the plastic shrinkage moulds, which are subsequently placed in the climate chamber for the full test period.

Table 1: Mix design for 3D printing

Constituents	kg
Cement CEM Ⅱ 52.5N	579
Fly ash	165
Silica Fume	83
Sand	1241
Water	232

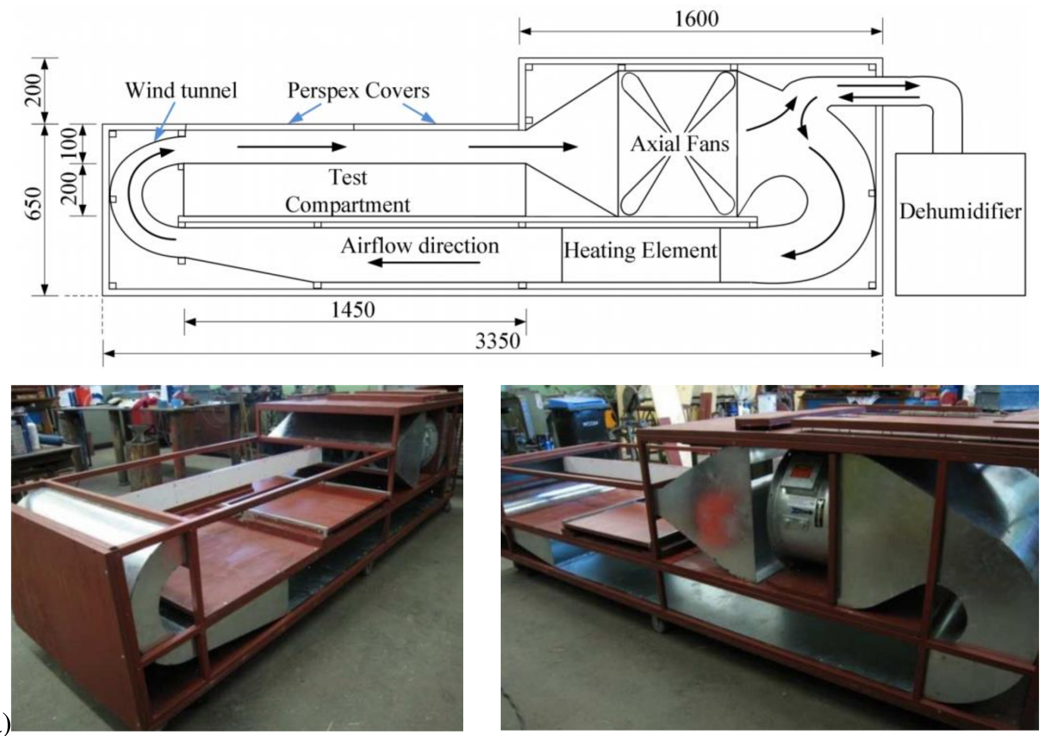
Plastic shrinkage results

The initial and final setting times are tabulated Table 2. It is found that the fibres do not have a noticeable influence on initial setting time. Note that these tests are conducted in the climate chamber at laboratory conditions, i.e. not while the extreme evaporation rate is simulated by high temperature, wind and low RH.

The two horizontal LVDT readings are collected and processed into horizontal shrinkage strain. The results are depicted in Figure 4. The fibre concrete is shown to have reduced plastic shrinkage. It should be noted that the plastic shrinkage found to be in the range 2.7 to 3.5 mm/m is low compared with typical, more standard concrete classes under these extreme evaporation conditions (Combrinck 2012).

Table 2: Setting time test results

Setting time (min)	Control	V_f = 0.15%	V_f = 0.3%
Initial	100	100	100
Final	160	140	160

(a)


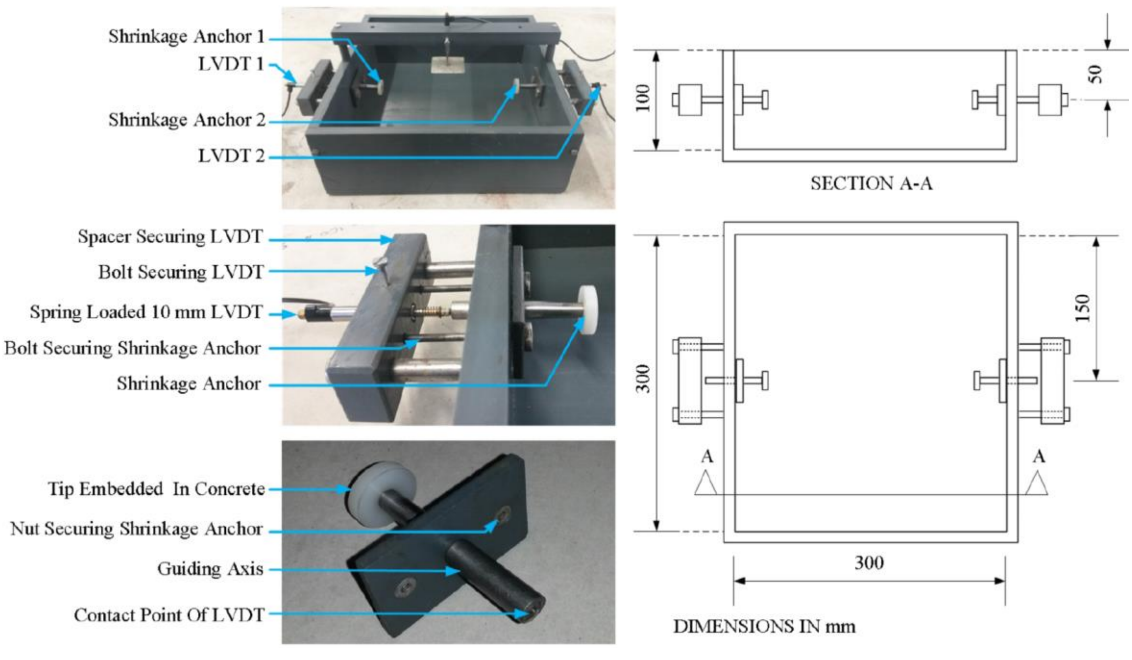
(b)


Figure 3: a) Climate chamber layout (Combrink 2012). b) Plastic shrinkage mould and setup (Le Roux 2016)

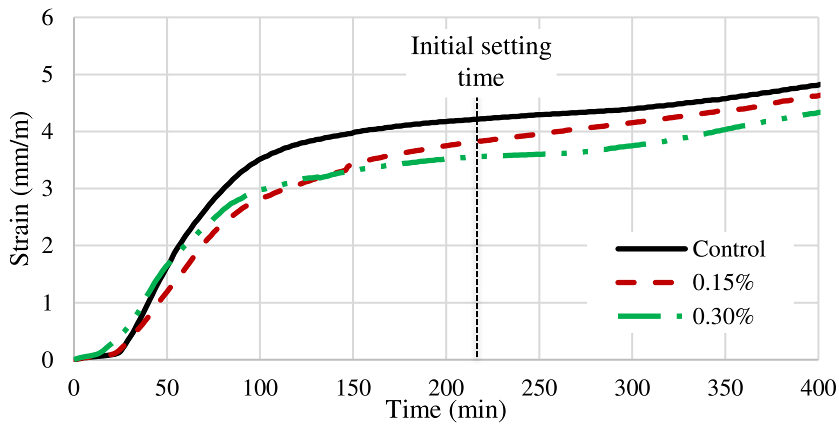


Figure 4: Plastic shrinkage test results, showing the average of three specimens per type

MECHANICAL STRENGTH AND STIFFNESS

Test Method

To characterise the mortar, and investigate the influence of the fibre reinforcement, standard compressive strength tests are performed according to SANS 5863 (2006). The cylindrical specimen with 100 mm diameter and 200 mm height is placed between the auxiliary steel top and bottom plates in a Contest Materials Testing Machine (MTM), and subsequently tested at a constant rate of 0.3±0.1 MPa/s. The MTM records the peak uniaxial force, which is divided by the cross-sectional area to obtain ultimate compressive strength.

The Young's Modulus is determined according to ASTM C 469 (2002). The cured cylindrical specimen is mounted in the Contest MTM, instrumented with a light test frame supporting three LVDTs with 70 mm gauge length, spaced at 120º around the cylinder circumference. An HBM 2 MN external load cell is placed between the specimen bottom face and plate to record the force. The specimen is loaded to approximately 40% of its compressive capacity while the deformation is recorded by the three LVDTs.

Specimen preparation

ASTM C 31 (2012) is followed to prepare cylindrical specimens with height-to-diameter ratio of 2, with the height and diameter of the cylinder 200 mm and 100 mm respectively. After casting the specimens in moulds, they are cured under laboratory conditions until stripping from the moulds after one day, and subsequently water-cured at 23±2ºC until a test age of 14 days. The test program studies strength and stiffness at various ages, but only 14 day strengths and stiffness are reported. Note that, after the Young's modulus test on a specimen, the LVDT instrumentation is removed, and the specimen tested further to obtain ultimate strength. These specimens represent the exact same mixes as used for the plastic shrinkage testing in the previous section.

Strength and stiffness results

The recorded forces and displacements are normalised to stress and strain and the results are summarized in Table 3. It is found that there is no noticeable influence due to fibre reinforcement on compressive strength and stiffness. This is ascribed to the low volume of fibre, which through the theory of mixtures to not contribute significantly to ultimate resistance of stiffness. The relatively high coefficient of variability (0.103) for compressive strength of the mix containing 0.15% volume of fibre may indicate poor dispersion of fibre, in contrast to the lowest coefficient of variability (0.020) for the mix with the highest (0.3%) fibre content. The variability in Young's modulus is also highest (0.073) for the 0.15% fibre volume mix, bearing in mind that the same specimens used for E-modulus were tested further for ultimate compressive strength. Improved, standardised mix processing control procedures are to be adopted to improve mix consistency.

In addition to strength and stiffness of the 3D printable cement-based materials, interlayer cohesive strength is important for transfer of shear stress across layers. This is the focus of continued research.

Table 3: Compressive strength, f_{cu} (MPa) and elastic modulus in compression, E (GPa) (with coefficient of variation in brackets)

	Control	0.15%	0.3%
f_{cu} (MPa)	77.15 (0.022)	72.28 (0.103)	77.40 (0.020)
E (GPa)	32.76 (0.066)	30.22 (0.073)	30.04 (0.013)

Note: Each sample consists of 4 specimens

3D PRINTING OF FRC

Specimens shown in Figures 5 and 6 were 3D printed to demonstrate progressively improved control and material performance. All prints were performed at a nozzle translational speed of 50 mm/s, before decelerating for translation to the next level height. Figure 5a shows the very first 3DPC specimen of the group on 3 May 2018, with the mortar material without fibre defined previously in the paper. Figure 5a shows irregular layer thickness and width due to inadequate printing control, especially where the nozzle height is adjusted to the next level.

The products of the next 3D concrete print on 21 May 2018, a near perfect cylindrical column of 47 layers (height 471 mm), and a 45 degree twisted square column of 60 layers (height 710 mm) are shown in Figure 5b & c. Details of overall specimen geometry and layer thickness are summarised in Table 4. The bottom layer average thickness is 21.5% and 7.3% respectively less than the top layers of the two specimens, as a result of layer deformation under the pressure caused by the weight of the layers above. Recall from Section 2 that the initial setting time for the mix is roughly 100 minutes, i.e. significantly longer than the duration of the 3D print, which means that the static shear flow resistance of the material is effective at limiting layer deformation. Finally, on 13 June 2018 the 3DP specimen shown in Figure 6 was produced with the fibre concrete mix described in Section 2 with $V_f = 0.3\%$.

Table 4 – 3D printed object geometry. Average of 2-4 readings (coefficient of variation in brackets)

Figure	Layers	Width (mm)	Height (mm)	3DP duration (min)	Average layer thickness (mm)		Remarks on material/control improvement
					Base	Top	
5a $V_f = 0$	40	-	-	13	-	-	Collapsed due to operator error
5b $V_f = 0$	47	402.5 (0.002)	478.0 (0.033)	21	11.9 (0.046)	9.3 (0.141)	Good quality surface, improved software control.
5c $V_f = 0$	60	257.5 (0.014)	701.0	23	11.6 (0.027)	10.7 (0.053)	Good print, but air sucked in at concrete feeder produced irregular layers
6a $V_f = 0.3\%$	70	250.5 (0.003)	792.5 (0.003)	26	11.9 (0.046)	12.6 (0.152)	Best print; but air sucked in at concrete feeder produced irregular layers

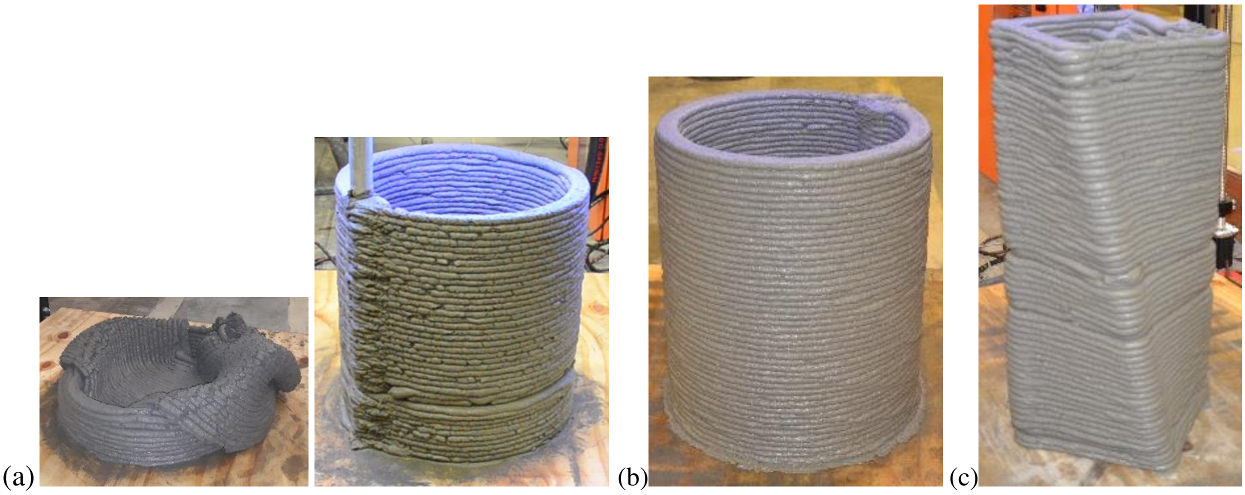


Figure 5: Progression in 3D concrete printing control and material rheology at SU: (a) Collapsed circular column through poor printer control, shown on the right before collapse to have poor surface quality due to inadequate rheology and pump speed control at onset of new layers; (b) improved layer uniformity and surface quality due to improved rheology and pump speed control at the onset of new layers; (c) increased height and geometrical complexity (45 degree twist) shown to be stable despite irregular layers due to pump feeder air ingress.

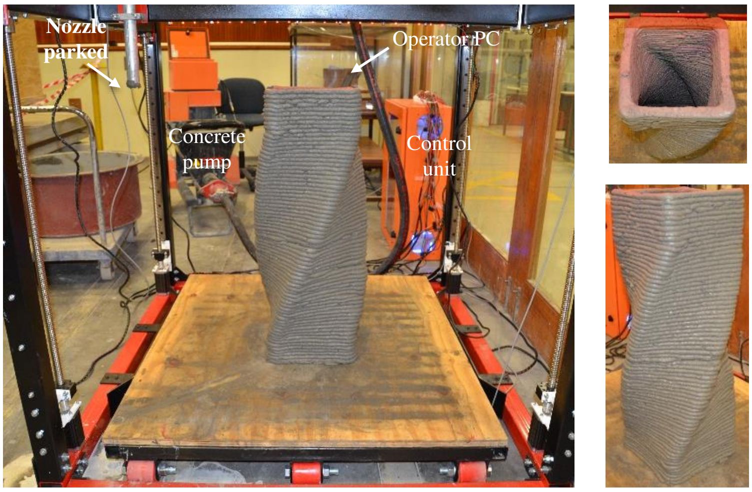


Figure 6: 3DP of fibre concrete column with a 90 degree twist over 0.6 m of the 0.8 m height of 70 layers, showing a top and side view on the right.

CONCLUSIONS

3DPC is a burgeoning research field allowing for the creation of innovative construction methods, technology and building materials. What is lacking in the current literature is the characterisation of the materials appropriate for 3DPC, as well as utilising advanced/high-performance composites together with this unique construction method. The 3DPC research team at Stellenbosch University has taken significant steps in the last 2 years in this regard, with the construction of the first gantry-type 3D printer on the African continent and preliminary tests on polymer fibre concrete for 3DPC. From the results, the following conclusions are drawn:

- The shrinkage is reduced by roughly 15% by the low volume of fibres at the time of initial setting. A marginal difference occurs between 0.15% compared to 0.30% of fibre volume at initial setting time.
- There is no noticeable influence of fibre reinforcement on compressive strength and stiffness at these low fibre volume contents.
- 3D printed prototypes demonstrate increasing construction control, as well as layer dimensional stability and overall structural stability by the addition of polymer fibre concrete at the low volumes considered here.

Future work will aim to introduce new material types for 3D printing and characterise these materials fully in the context of 3DPC.

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